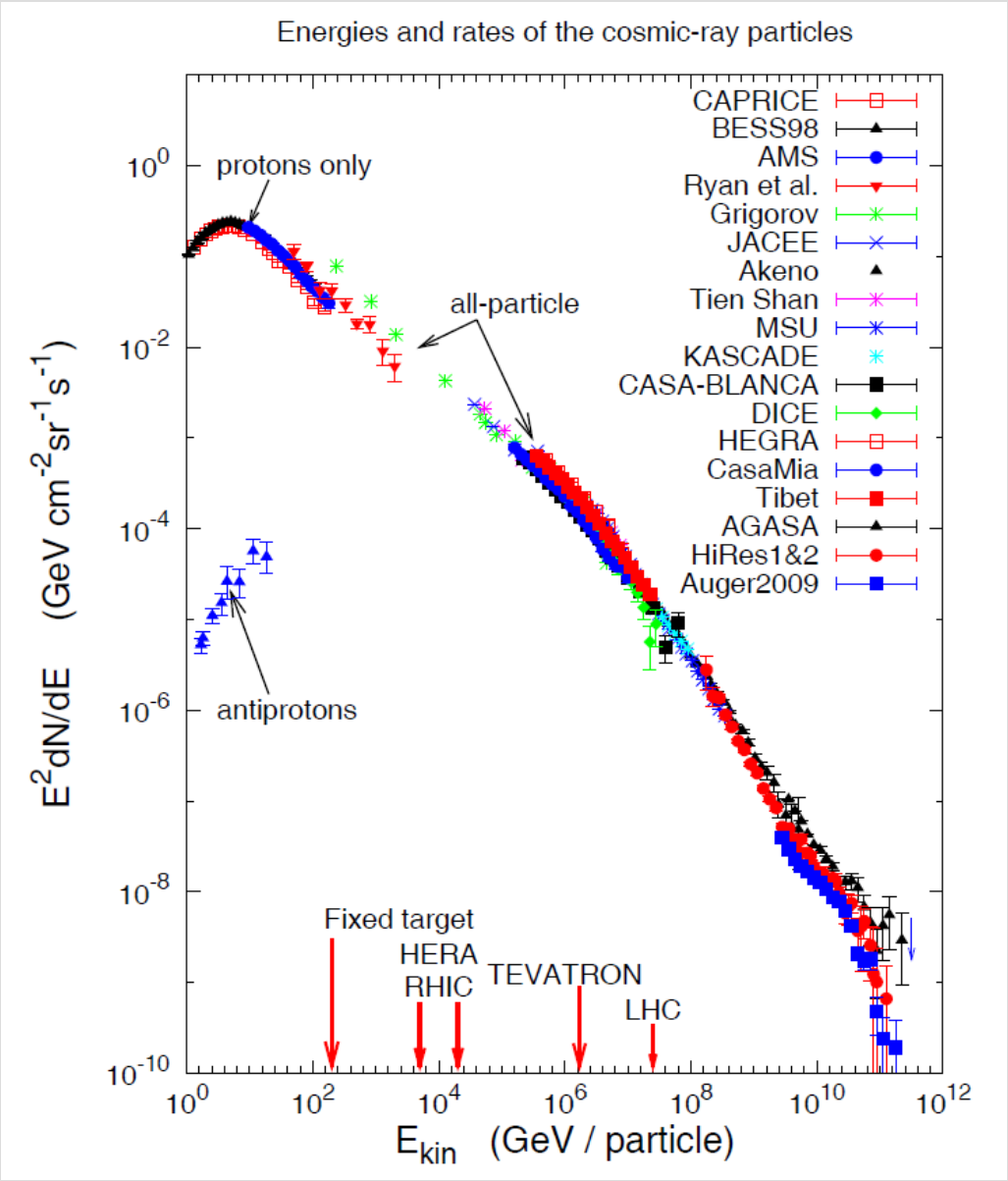
Cosmic rays and particle physics

- 1912: Hess discovers cosmic radiation
- 1930's: E-W effect → proton primaries
  - Discovery of positron, muons
- 1940's: Discovery of pion, kaon
- 1950's: Knee of spectrum, diffusion model, SNR as source of power for cosmic rays
- 1960's Ankle of spectrum → extragalactic CR
  - CMB → prediction of cosmological feature (GZK "cutoff")

Why is progress so slow?

- Low flux
- Indirect experiments
- 2008: HiRes sees "cutoff"
- 2009: confirmed by Auger
- But what does it mean?



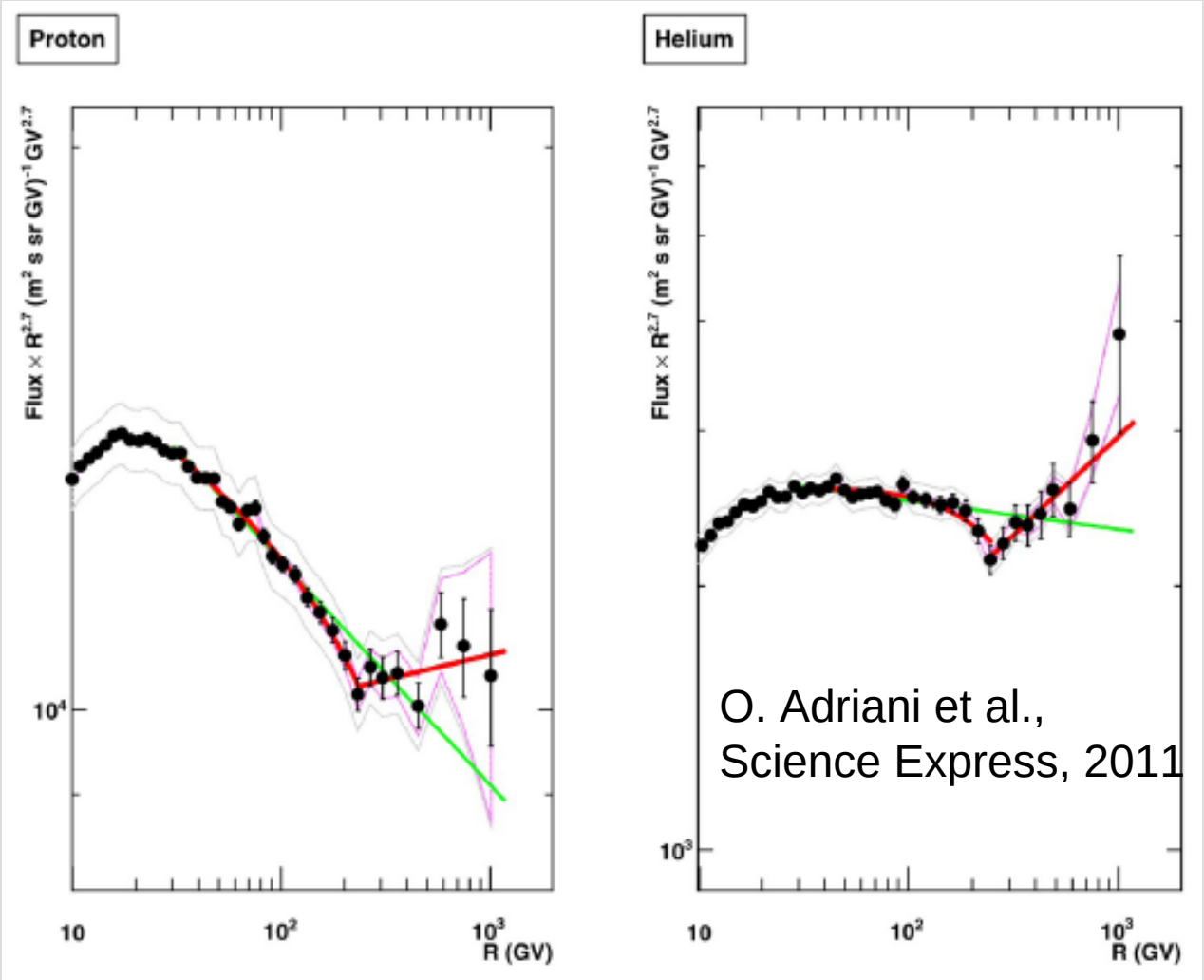
Galactic cosmic rays

- Powered by supernova explosions
- Non-linear shock acceleration
  - Complex spectrum, complex source regions
  - Not simple Fermi acceleration with E^{-2} spectrum
  - ATIC, CREAM, PAMELA show spectral features < knee
  - AMS-II is next
- Knee is a property of the spectrum, not new physics
- Look for $\pi^0 \rightarrow \gamma\gamma$ / π,K$\rightarrow \nu$ from galactic sources
  - Fermi, VERITAS et al. (CTA is next)
  - IceCube

Unexpected details revealed in precision measurements

Rigidity spectra of protons & He from PAMELA

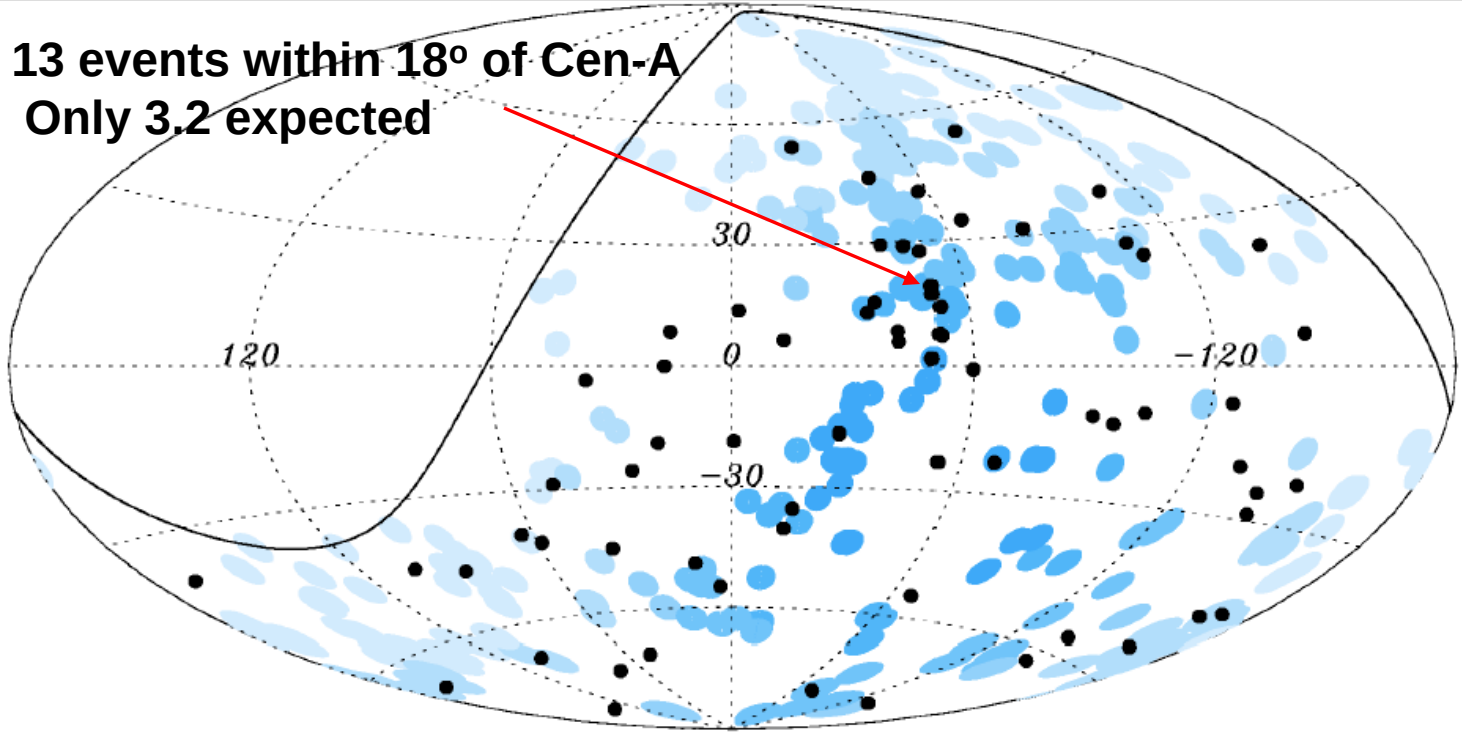
- Proton & helium spectra are different
- Structure suggest two populations of particles, e.g. from different sources
- Consistent with hardening seen by ATIC & CREAM with less resolution



Lessons for high energy

- Expect multiple populations/sources
  - Different spectra, different compositions
- Indirect measurements > 100 TeV
  - Poor resolution of air shower detectors compared to direct measurements
  - Use energy-dependence of main nuclear groups as a proxy for precision spectrometer measurements of elemental abundances

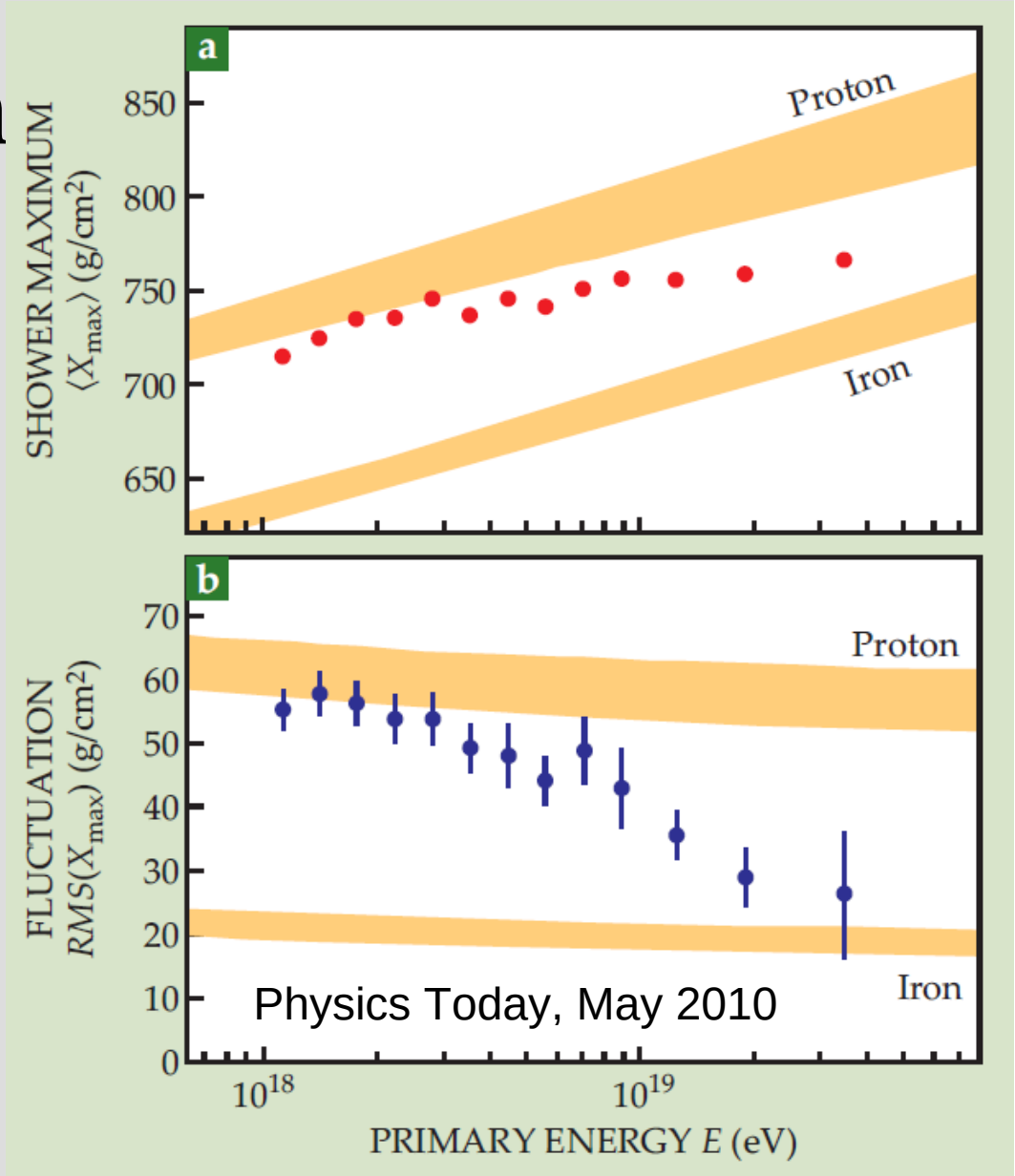
Auger anisotropy E > 50 EeV



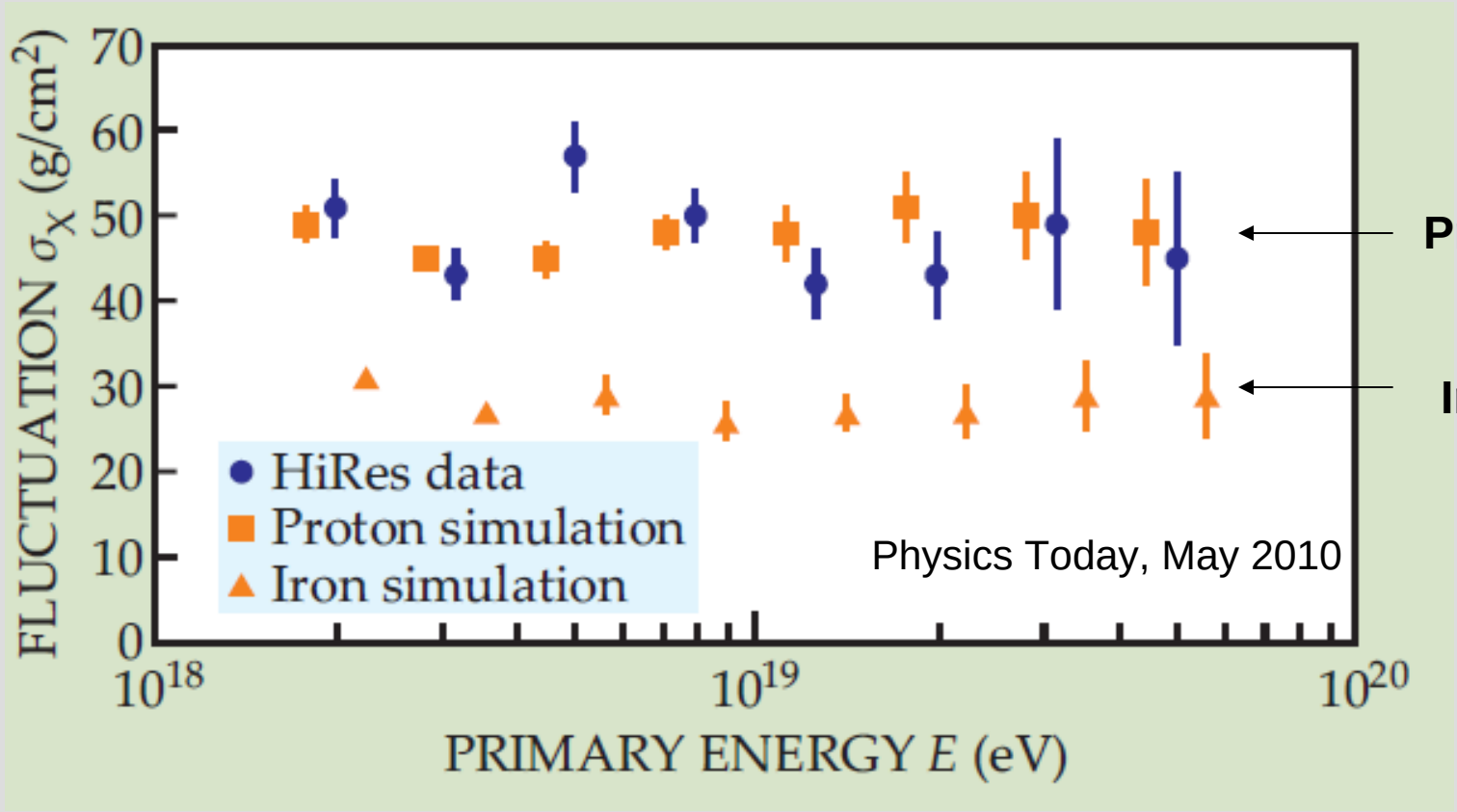
Auger Collaboration, Astropart. Phys. 34 (2010) 314–326

Auger spectrum & composition E < 40 EeV

- Tension with anisotropy
- Xmax suggests transition to Fe
- Anisotropy needs protons

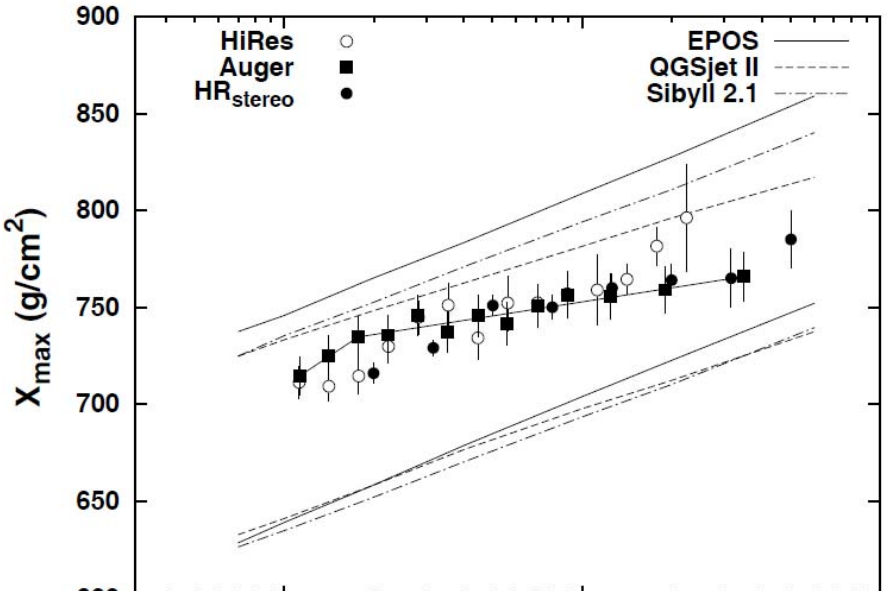


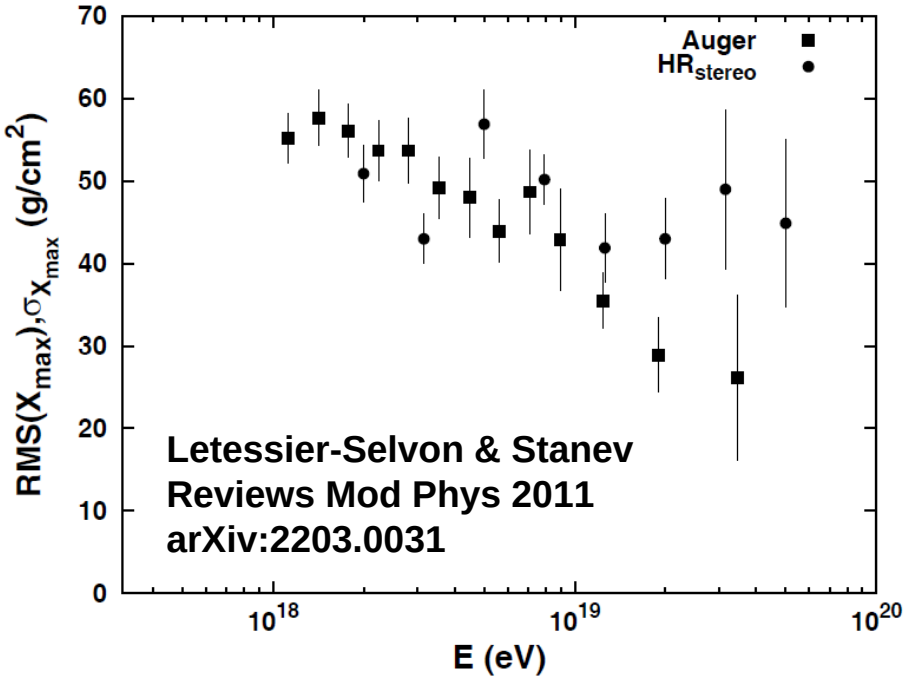
HiRes Xmax & σ_{xmax} reach a different conclusion



Compare Auger & HiRes

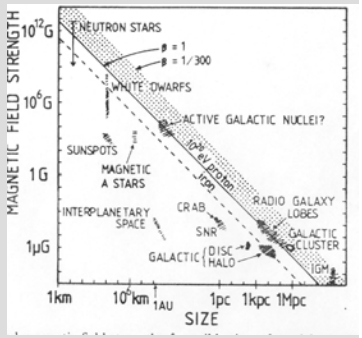
- Differences only $10 < E < 50$ PeV
- HiRes: stereo fluorescence
- Auger: hybrid SD + fluorescence
- TA also hybrid
  - Results pending





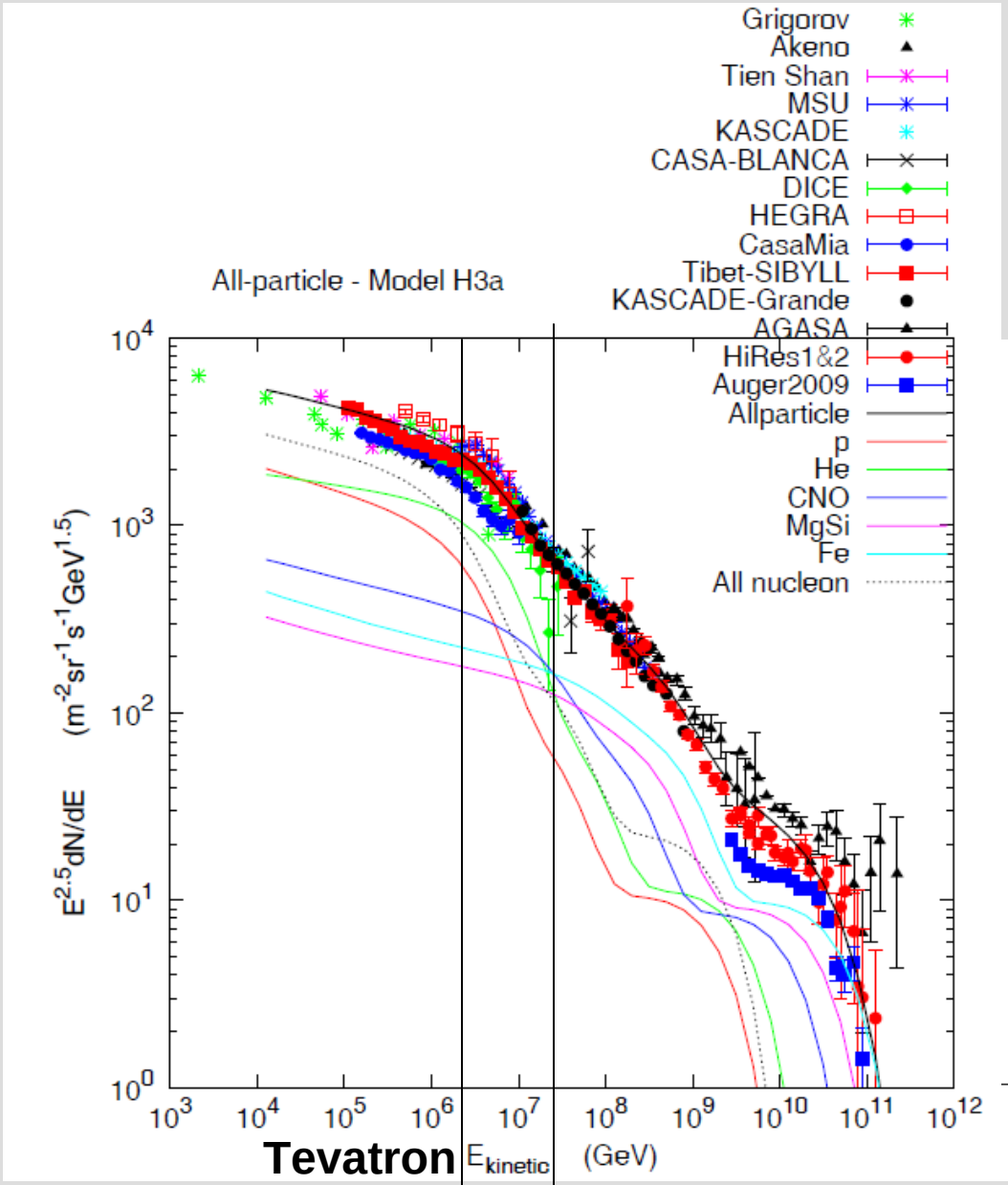
Comments on UHECR

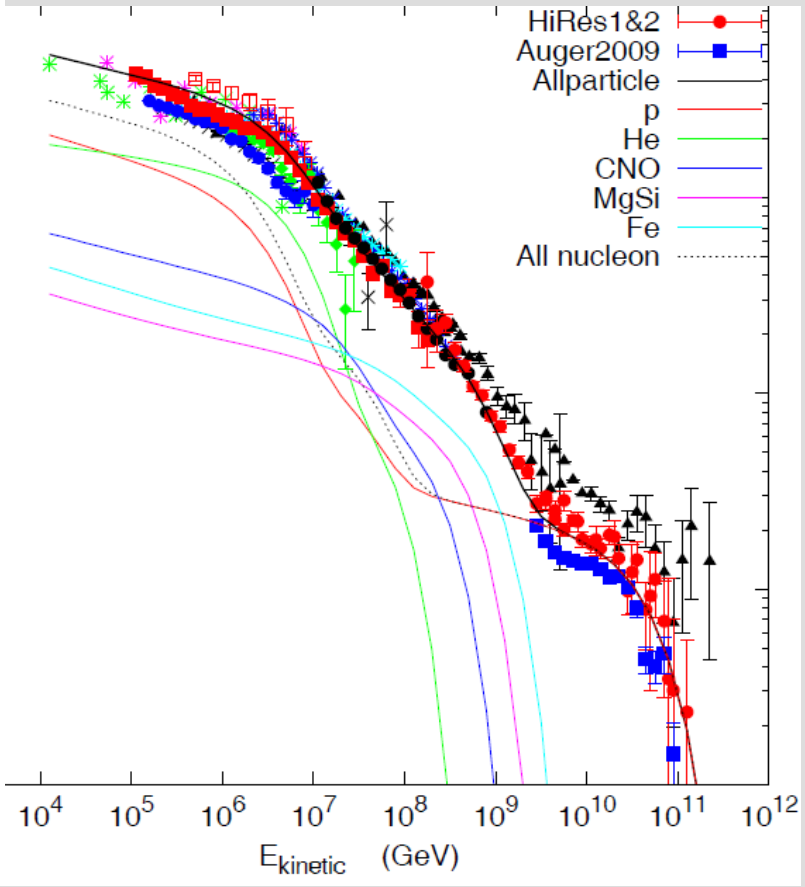
- Spectrum steepens for E > 50 EeV
  - Confirmed by both Hi-Res and Auger
- Interpretation of "cutoff" is not clear
  - Could be the long-sought "GZK" effect due to energy losses of particles from sources at cosmological distances
  - Could also be the accelerators reaching E_{max} (remember the Hillas plot)



- Measurements of composition are key
  - From < EeV to see transition to extragalactic CR
  - Current conflicting interpretations (HiRes, Auger)
  - Several experiments address this question

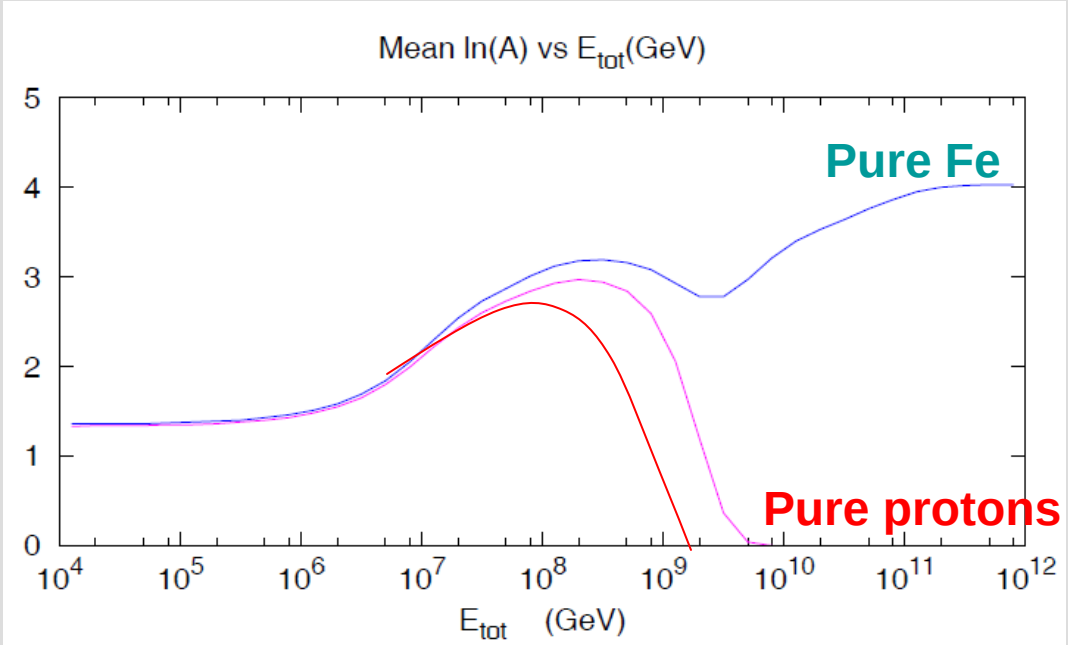
Two extreme possibilities





Compare extremes

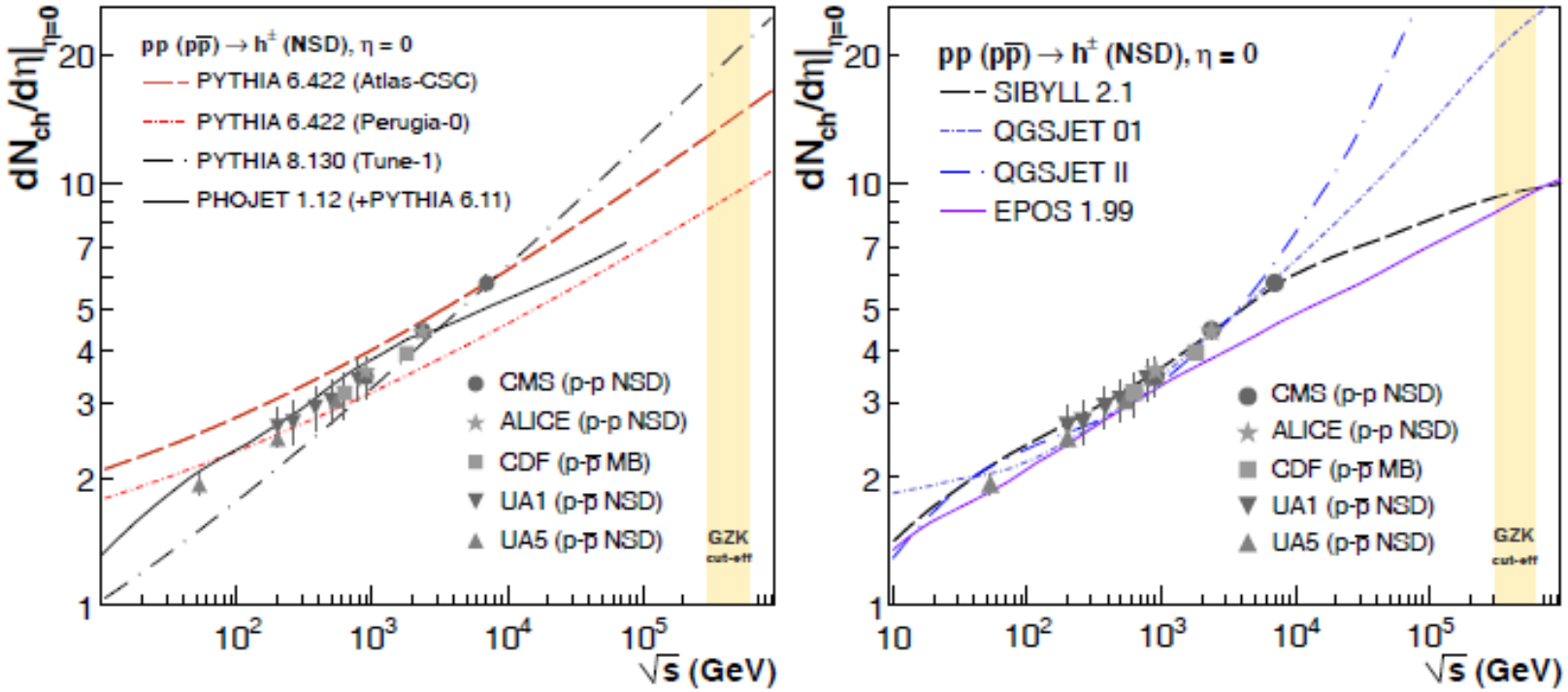
- Model A
  - E_{max} (p) ~ EeV
  - Local sources
  - All Fe at 50 EeV
- Model B
  - E_{max} (p) ~ 100 EeV
  - GZK cutoff



- Model C: mixed composition from distant sources
  - Would show up as p + Fe at Earth
- Experiments for composition < EeV:
  - Auger (AMIGA, HEAT), TA (TALE), IceCube, KASCADE-GRANDE, TUNKA

Hadron production at LHC

Collider models **Air shower models**



D'Enterria, Engel, Pierog, Ostapchenko, Werner arXiv:1101.5596v2

Central region only so far

LHC ←→ cosmic rays

- LHC for first time extends pp collisions beyond knee of cosmic-ray spectrum
  - Confirms knee as astrophysical
- Forward physics at LHC will be important
- Auger, Telescope Array probe hadron production to $\sqrt{s} \sim 100$ TeV
  - $E_{lab} \sim 5$ EeV
  - Gross features only
    - Cross section, inelasticity, multiplicity …

Remote sensing of large air showers

Technique	Pre-history	Externally triggered	Self-trigger
Fluorescence (Auger, HiRes, Telescope Array)	Greisen, 1960s	Volcano Ranch, 1977	Fly's Eye, Utah, ~1980
Radio (LOFAR, Codalema, Auger, RASTA)	Harold Allan, 1960s	LOPES, ~2005	ANITA ? 2010 Auger 2011 ?
Radar	Blackett & Lovell, 1940	Takai, BNL, Bi-static radar at TA in Utah	
Microwave (MIDAS, AMBER)	Russia, 1960s (molecular bremsstrahlung)	Testing this year at Auger	

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